The 20-Minute Flight Tests

Mujahid Abdulrahim*
University of Missouri Kansas City

Russell E. Erb[†] and Tyler G. Sanders[‡]
United States Air Force Test Pilot School

Flight testing an aircraft to evaluate performance and dynamic characteristics is an exercise which requires a skilled pilot, calibrated instrumentation, favorable weather conditions, and a substantial test campaign. The variability in any one of these factors can have a substantial impact on the quality of the results. With deference to the traditional and correct approach to aircraft flight test, what value could come from an abbreviated evaluation of an unfamiliar aircraft performed with an inexperienced test pilot and portable flight data instrumentation? The 20-Minute Flight Test project is an effort to explore the usefulness of such a hurried test campaign. Specifically, the authors have commissioned 20-minute flight tests with aviators in more than 20 different aircraft types. The educational goal of these flights is to help illustrate the relationship between aircraft configuration and resulting performance for students of Aircraft Design and Flight Test Engineering. Flight data results are compared to published values in the respective aircraft flight manuals to gauge the accuracy of the performance estimates compared to those from the manufacturer. The aim of the project is not simply to recreate part of a flight manual, but to help underscore to pilots and engineers the differences in performance and handling that comes from airframe design choices. More broadly, this form of test flight has practical application for pilots and engineers assessing the performance and characteristics of a new aircraft type in the presence of significant time constraints.

I. Introduction and Approach

The University of Missouri Kansas City offers an Aircraft Design class with a follow-on course teaching Flight Test Engineering methods. Students taking these courses frequently question the design choices made for particular, historical aircraft and wonder what effect those choices may have had on the flight performance and operational utility. The 20-Minute Flight Test campaign grew out of an attempt to illustrate the connection between aircraft design configuration and flight performance. In the single-engine aircraft category alone there are hundreds of different aircraft types - each inevitably a compromise between one part of the flight envelope and another. Why should there be hundreds of aircraft types? And why should there be such a large variation in the purchasing choices of pilots? What makes a particular aircraft choice well-suited for some missions and a poor choice for others?

The authors admit, with some humility, that it is generally rude to invite oneself into the home, car, or airplane of another. With apologies to social tact, the authors did exactly that in an attempt to fly in as many aircraft types as possible. Each volunteer aircraft owner and pilot agreed to take an author on a short flight conducting a set of simple maneuvers. Additionally, each owner/pilot answered a set of questions about their particular airplane choice and what, if any, changes they might make if given a chance to redesign it.

In most cases, the volunteer pilot is the owner of the test aircraft and likely chose to purchase and own that specific model because of fitness to an individual flying mission. The only qualifications sought is the pilot be appropriately certificated and rated for the aircraft and have the necessary currency and proficiency to conduct the flight. The volunteer pilots ranged in experience from low-time private pilots to Air Force Test Pilot School instructors with many thousands of hours of flying experience.

Flight tests for performance characterization usually require highly-instrumented aircraft flown by experienced test pilots performing precise maneuvers in specific, quiescent flight conditions. Conversely, the 20-Minute Flight Test project employs unfamiliar aircraft flown by pilots without any flight test experience in a range of weather conditions.

---

*Associate Professor, AIAA Associate Fellow
[†]Aircraft Performance Master Instructor, AIAA Senior Member
[‡]Flight Sciences Branch Chief, AIAA Senior Member

A portable flight data instrumentation system is mounted externally on the aircraft with measurements for airspeed, altitude, angular rates, acceleration, and position.

Considering the adverse circumstances of the flight tests, the flight card is to designed to include maneuvers that are relatively insensitive to piloting technique. The pilots are requested to fly the maneuvers in a way that shows the fundamental response of the aircraft. These core responses can be used to estimate the performance capabilities of the aircraft without depending on direct measurements that might vary considerable with piloting technique. Any pilot can then perform the 20-Minute Flight Test maneuvers and yield meaningful flight performance measures, albeit with greater uncertainty compared to a properly-executed test campaign.

II. Motivation

What practical value could come from a flight test not much longer than a decent bowel movement? Isn't it likely that those two things produce similar outcomes?

The authors make no claim that the abbreviated flight test discussed in this paper provides a new flight test technique or is expected to replace the careful and methodical approaches used in experimental and certification flight testing. However, a shortened flight test can find practical use, apart from the educational value, in reassessing known aircraft after minor modifications or when a pilot is evaluating an unfamiliar aircraft. In both cases, the format of the 20-Minute Flight Tests provides an opportunity for the pilot to explore the aircraft over much of the flight envelope. In doing so, the pilot and flight test engineer can assess the characteristics of that aircraft for the purpose of performance estimation for flight planning, comparison with other aircraft, or for pilot familiarization.

There are three notable instances where short, comprehensive flight tests can be applied effectively. The first instance is for initial flights of an aircraft after modification or maintenance. The aircraft may have been modified according to a supplementary type certificate (STC), experimental modification, repairs, rigging, or other change to critical parts of the aerodynamic, propulsion, or control systems. The aircraft may also have undergone an annual inspection (or condition inspection) and was reassembled, possibly with some components replaced. In this instance, the initial test flight on return to service should evaluate whether and how the modification or maintenance has affected the performance and handling of the aircraft.

In the second instance, aircraft may need to be ferried after maintenance or sale by a pilot unfamiliar with the specific airframe or perhaps the model type. In this case, the pilot is presumed to be a proficient, experienced pilot and could perform the flight test to become familiar with the performance and handling of the aircraft. The results of the flight test would be used in flight planning to determine acceptable routes, climb gradients, runway lengths, and handling characteristics.

In the third instance of applicability, flight instructors performing aircraft checkouts can use the short flight test format to assess the flying abilities of the students over the range of flight conditions. In this application, the maneuvers are used as an assessment of the pilot, rather than the aircraft. Instructors can then address student deficiencies in the required part of the flight envelope prior to approving the student for solo flight.

III. Flight Card

Figures 1 and 2 show the flight card used for the 20-minute flight tests. The card is designed to print on a single, double-sided sheet of paper and be used for both briefing the maneuvers with the volunteer pilot and for logging the data.

Figure 3 shows a time history of the flight data with colored annotations corresponding to the maneuver times.

Each of the subsections describes the specific philosophy behind the maneuver design.

A. Test Card 1: Takeoff Performance

Test Card 1 consists of a normal takeoff or any takeoff variation, at the discretion of the pilot. The important aspect is for the pilot to use maximum takeoff power so that the aircraft can be observed accelerating from slow speed to rotation speed. Instructions are specifically vague during this test so that pilots can perform their typical takeoff maneuvers and are not subjected to unfamiliar protocols during a critical flight phase.

It is not critical that the pilots attempt to perform a minimum-length takeoff or rotate at a particular speed. Instead, the projected minimum takeoff length can be estimated using the takeoff acceleration profile combined with the measurement of stall speed.

The observed takeoff acceleration is specific to the weight and density altitude at the time of test. The performance can be extrapolated to other weights and density altitudes by estimating the influence of incremental changes to the

Fig. 1   Flight Test Card (Frontside), Including Aircraft Data and Pilot Questionnaire

Fig. 2   Flight Test Card (Backside), Including Maneuver Guide and Data Sheet

performance normalized by the current conditions.

B. Test Card 2: Climb Performance

The climb performance is assessed during short-duration climbs at three characteristic airspeeds, including V_x for maximum angle of climb, V_y for maximum rate of climb, and V_{cc} for a typical cruise climb. The duration of each climb is limited to 30 to 60 seconds, which admittedly is shorter than that used for traditional sawtooth climb tests.

The pilots are instructed to fly at particular climb speeds according to recommendations from their pilot operating
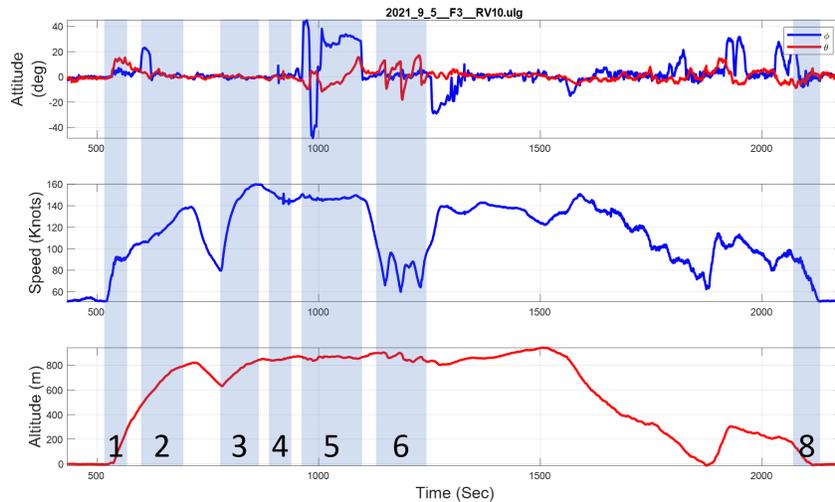
Fig. 3   Time History of Flight Data With Maneuver Overlay

handbooks or personal experience. The intent of the climb performance maneuvers is not necessarily to identify specific, optimal airspeeds, but rather to measure the climb rate when flown at particular, pre-specified speeds. This data can be used to determine relative differences in climb angle and climb rate between the three speeds, in addition to providing a baseline comparison with data from the level acceleration.

Data from the climb performance tests is inherently subject to errors from atmospheric conditions. The short duration of the tests combined with the limited availability of the pilot and aircraft mean that performance variation from local atmospheric conditions cannot be controlled.

C. Test Card 3: Level Acceleration

The level acceleration test card assesses the aircraft response to excess power over the entire speed range. Pilots are asked to trim the aircraft at an intermediate cruise speed, then decrease speed to near-stall slow flight while maintaining altitude. Once established and trimmed in slow flight, the pilot then applies maximum continuous power and allows the aircraft to accelerate at a fixed altitude. Both the pilot and the flight test engineer monitor the instruments and determine that the maneuver is complete when the airspeed converges to the maximum level flight speed.

The level acceleration is not a maneuver typically flown by pilots inexperienced in flight test methods. The consequence of this inexperience is typically variations in altitude as the pilot adjusts trim through the airspeed range. Using energy method performance analysis, these altitude variations can be accounted as energy exchange. The expected output of the maneuver is a measure of specific excess power versus airspeed. Specific excess power can be measured both as an acceleration and as a climb rate, so the maneuver need only converge to a fixed energy state.

D. Test Card 4: Control Response

The control response flight card asks the volunteer pilots to perform uncoupled, uncompensated input doublets to the ailerons, elevator, and rudder control surfaces. Pilots are briefed on doublets as a type of flight test maneuver on the ground, then asked to perform the doublets in flight.

The response of the aircraft to control doublets evaluates the primary-axis control response, cross-axis coupling, and subsequent oscillations after the pilots have returned to stick-fixed condition. Pilots that are accustomed to coupling controls, in particular rudder with aileron inputs, are briefed to perform the doublets on one axis at a time and to return to stick-fixed inputs following the completion of the doublets.

Aileron doublets illustrate the degree of adverse yaw during uncoupled inputs and also demonstrate the relationship between roll control forces and resulting roll rates.

E. Test Card 5: Turn Response

The turn response test card evaluates the maneuverability of the aircraft using a sequence of turns, including opposite direction 90° turns and one 360° steep turn. Pilots are instructed to use maximum roll control in transition between the two 90° turns in order to identify the maximum roll rate capability of the aircraft. The steep turn is used to assess the longitudinal stability and determine the control force per G maneuvering gradient.

The steep turn is also used for pitot-static system calibration. By comparing the airspeed against groundspeed, the airspeed measurement system can be corrected for calibration and installation errors.

F. Test Card 6: Stall Characteristics

The stall test card includes measurement of the level flight stall speed with power-off with flaps extended, power-off with flaps retracted, and power-on with flaps retracted. Measurement of the stall speed can be corrected for load factors different than 1[1]. Stall characteristics for each condition are assessed by observation, pilot comments, and data measurements.

Figure 4 shows a time history of the power-off stall maneuvers performed with the flaps retracted and extended.
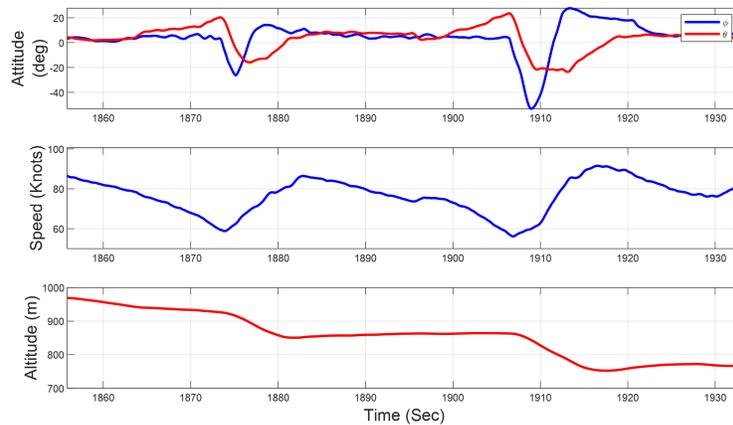
Fig. 4   Time History of Power-Off Stall Maneuvers Flaps Retracted and With Flaps Extended

G. Test Card 7: Maneuvering

The maneuvering test card is an open, undefined maneuver that permits pilots to showcase any aircraft capability that has not already been assessed in the other cards. For appropriately certified and configured aircraft, this maneuvering may include aerobatics or other maneuvers subject to the pilot's abilities.

H. Test Card 8: Landing Performance

The final test card assesses the landing performance of the aircraft. The pilot is asked to perform a normal landing. The obstacle clearance and landing distances can be estimated from the stall speed measurement and an approximation of the maximum braking force based on the geometry of the aircraft.

IV. Aircraft

The aircraft used in this study were based on the types owned by pilots who were willing to participate. The authors are not aware of any correlation between aircraft choice and personality, so there was no intentional bias apart from availability. Aircraft are designed, marketed, and sold to meet a set of requirements that represent the anticipated mission of the owner. These requirements could dictate handling qualities, speed, passenger capacity, minimum runway length, maneuverability, or many other factors. Choosing any particular aircraft to own and operate represents a compromise in capability and, practically speaking, a cost constraint.

It is not simply the hubris of individual aircraft designers that has led to the numerous variations of available aircraft

types. Designers do enjoy naming aircraft after themselves, to be sure, but there are also practical reasons to design aircraft with different wing spans, airfoil shapes, engine sizes, and seats. Each particular combination of design features yields an aircraft that meets a specific mission criteria and market.

Any design choice meant to improve performance in one area of the flight envelope will result in some compromise in another area. There is no "best" airplane, exceeding the capabilities of all lesser aircraft in all performance metrics. Some of the core measures of performance for powered aircraft are power loading (engine power per weight) and wing loading (weight per wing area). Figure 5 shows a plot of these two parameters for the aircraft used in this study, with data obtained from the respective pilot's operating handbook or aircraft flight manual[2][3][4][5][6][7][8][9][10][11][12][13][14]. The aircraft are indicated by a colored marker, listed in the legend in order of increasing wing loading. This format for presenting data is used elsewhere in this paper, although the aircraft order and associated marker colors may differ between plots.
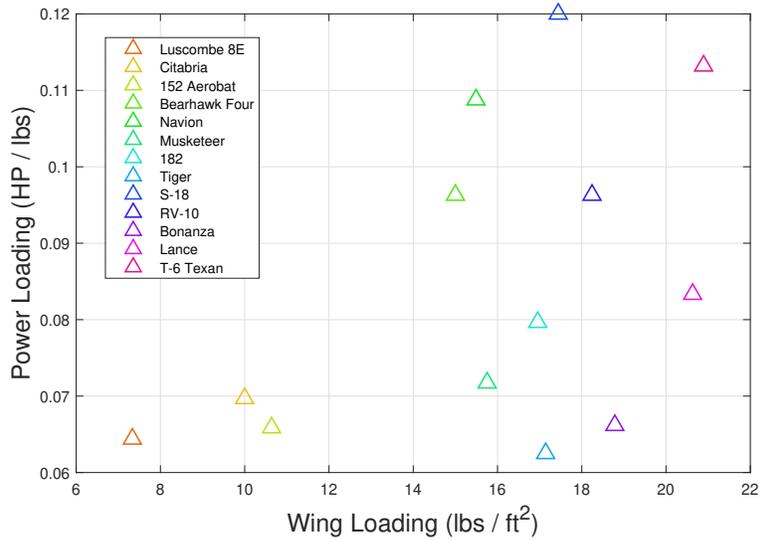

Fig. 5   Power Loading vs Wing Loading for Tested Aircraft

Pilots wishing to fly at fast speeds with fast climb rates may desire an aircraft with a high power loading, giving a relatively large engine compared to the weight of the aircraft. Pilots wishing to land on short runways may desire aircraft with low wing loading, while others wanting to fly efficiently at fast speeds may opt for higher wing loadings. Light, two-seat aircraft such as the Luscombe 8E, Citabria, and Cessna 152 are clustered in the lower left of the plot, with low power loadings and low wing loadings. To the very right of the plot are the aircraft with the highest wing loadings, with the North American T-6 Texan having nearly the same wing loading as the Piper Lance. The power loading of the T-6 is nearly 50% higher than that of the Lance, partially explaining the wartime utility preference for the T-6.

The usefulness of aircraft is measured by more than just the maximum speed. Whether in the case of a family trip or evacuation during a zombie apocalypse, a useful aircraft is one that can carry people quickly to a destination and, once there, be able to safely land in a constrained area. Figure 6 shows the speed utility of an aircraft compared to the required landing distance. Speed utility is a measure of how fast an aircraft can move a group of people. A four-seat aircraft flying at 100 knots has a speed utility of $400\,person - knots$, the same utility as a two-seat aircraft flying twice as fast.

The Piper Lance has the highest speed utility of the tested aircraft, capable of carrying 6 passengers at 140 knots. The lowest speed utility is provided by the Luscombe 8E, ferrying two people at speeds less than 100 knots. The ability to escape the undead cannot be the only measure by which an aircraft is assessed, and neither the current discussion nor any list of specifications can completely explain the appeal of a particular aircraft design to a pilot. That appeal could include some or all of the performance measures in addition to aesthetics, cost, maintainability, and availability. Figure 7 shows photos of the aircraft used in this study which are, admittedly, a very small segment of the set of airplanes the authors would like to test someday.
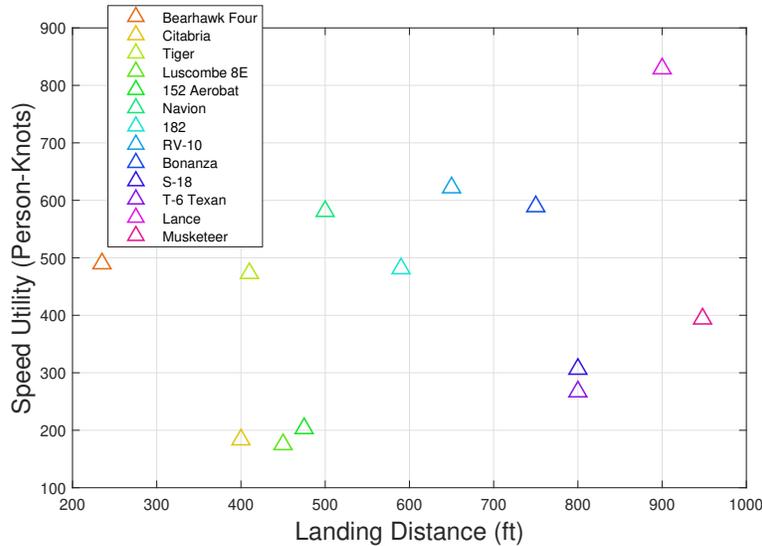
Fig. 6   Speed Utility vs Landing Distance for Tested Aircraft

V. Aircraft Performance Measurements

The specific set of maneuvers on the condensed, abbreviated flight test are designed to identify common performance characteristics for the aircraft, even in cases with small errors in maneuver execution. The sequence of these maneuvers is designed to keep the aircraft close the airport, airspace permitting, and data from several maneuvers can be combined to estimate the aircraft performance parameters. Table 1 shows a list of some aircraft performance measures and the corresponding flight test maneuver(s). The reference in 14 CFR Part 23 for each of the performance measures is shown in parentheses.
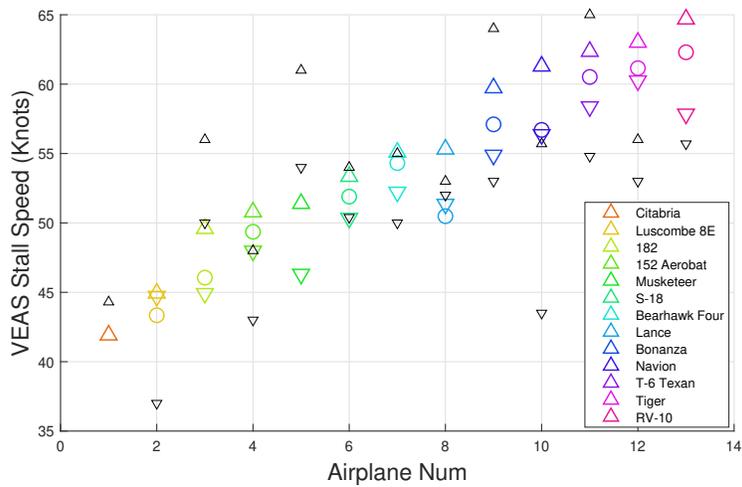
A. Stall Speeds

Certified aircraft are required to identify the stall speed, defined in 14 CFR 23.2110[15] as the minimum steady flight speed at both idle thrust and nominal thrust. The regulation does not specify whether the aircraft should be in descending, level, or climbing steady flight, although practically the aircraft will be in a steady descent for idle thrust and in level flight for nominal thrust. The critical condition for stall speed tests is at maximum gross weight and maximum forward center of gravity position. Stall speed measurements in the 20-Minute Flight Tests are not controlled for weight or center of gravity, although these values are known and used in the flight data reduction.

Pilots perform up to three types of stalls during the flight test, including power off with flaps up, power off with flaps (and landing gear) down, and power on with flaps up. In some cases, the aircraft may not be equipped with flaps or the pilot may feel reluctant to perform a power-on stall. In these cases, no data is shown for the corresponding stall type. Figure 8 shows a comparison of the stall speed measurements for each type of stall on each aircraft. The stall speeds are corrected for both weight and density altitude such that the results estimate the stall speeds for an aircraft loaded at maximum takeoff weight weight at sea level. Upward-facing triangle markers show V_{S1}, stall speeds in knots with power off and flaps up. Downward-facing triangle markers show V_{S0}, stall speeds in the landing configuration with power off and flaps down. Circular markers show V_{S2}, stall speed with power on and flaps up. Colored markers represent data from the flight test measurements, while black markers show data from the respective airplane flight manual.

Comparing the measured stall speeds against the speeds listed in the airplane flight manuals shows errors of 10% or greater in some instances. Those errors could be a result of pitot static system calibration in the flight data instrumentation system, or related to changes in the aircraft compared to the factory test conditions. The airspeed calibration during the flight test focused on the 360-degree turn and other parts of the flights above moderate airspeeds and with good GPS data. Airspeed errors deviating from the calibrated values may be exacerbated at high angles of attack, particularly considering that the installation of the data logger on the exterior of the aircraft depended on the availability and location of tie-down loops and was not subject to careful calibration across the range of flight conditions, as in the case of factory pitot-static systems.

7
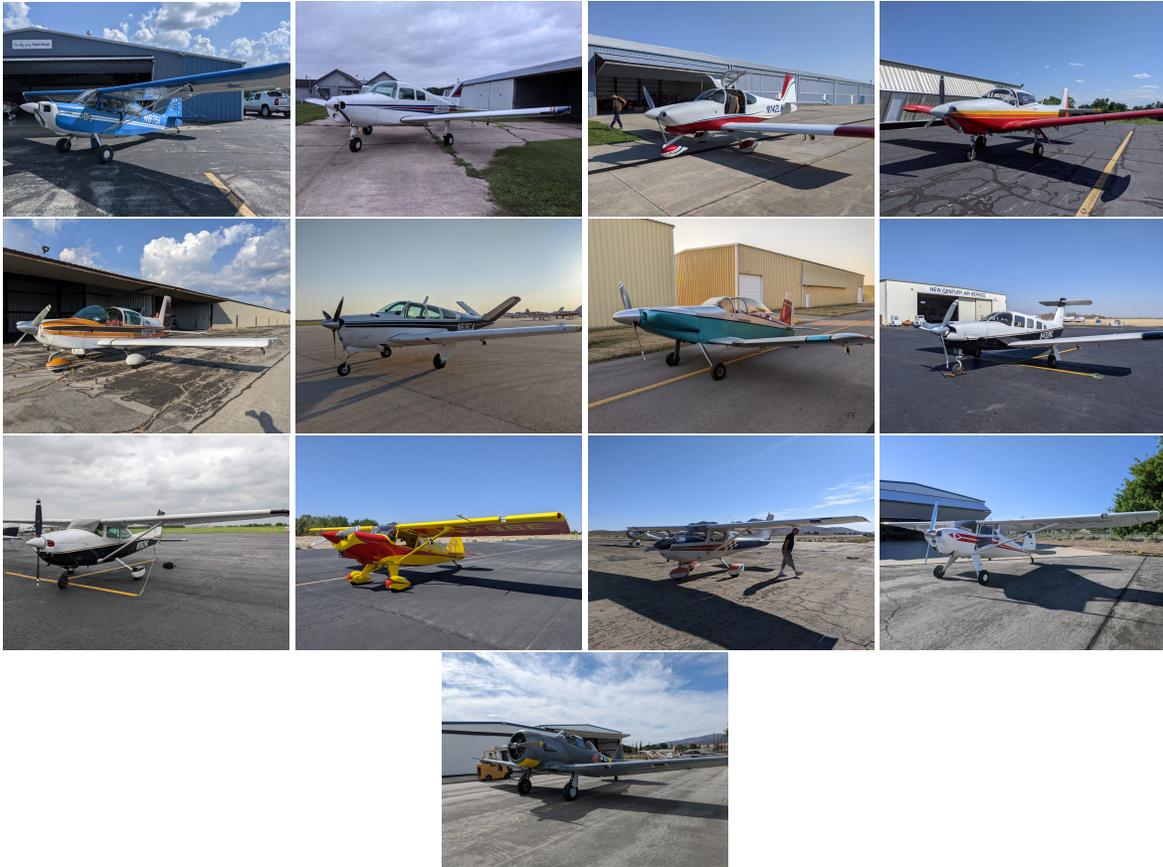
Fig. 7   Aircraft evaluated in 20-minute flight tests. Left to right, Top row: American Champion Citabria, Beechcraft Musketeer, Vans RV-10, Ryan Navion. Second row: Grumman Tiger, Beechcraft Bonanza, Thorp S-18, Piper Lance. Third row: Cessna 182, Bearhawk Four, Cessna 152 Aerobat, Luscombe 8E. Fourth row: North American T-6 Texan

Fig. 8   Stall Speed Measurements for Power-Off Flaps Down, Power-Off Flaps Up, and Power-On Flaps Up

Parameter	FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8
Takeoff Distance (23.53, 23.59)	✓					✓		
Landing Distance (23.75)						✓		✓
Power Required		✓	✓					
Specific Excess Power		✓	✓					
Stall Speeds V_s, $V_s o$ (23.49)						✓		
Stall Characteristics (23.2150)						✓		
Climb Performance V_x, V_y (23.63)		✓	✓					
Stick Force per G (23.155)				✓	✓			
p_{max}, τ_{roll} (23.157)				✓				
Dutch Roll $\omega_{n,DR}$, $\zeta_D R$ (23.2145)				✓				
Airspeed Calibration			✓		✓			

Table 1   Aircraft Performance and Test Metrics Matrix with Associated Flight Card. 14 CFR Part 23 References Are Shown in Parenthesis

The maximum lift coefficient corresponding to the three stall configurations can be estimated using Equation 1 using the known aircraft specifications in addition to the weight-corrected and altitude-corrected flight data.

$$C_L = \frac{Wn}{\frac{1}{2}\rho V^2 S} \tag{1}$$

Figure 9 shows the maximum lift coefficient estimates during the three stall tests. The marker convention is the same as that used in the stall speed plot shown in Figure 8, where the upward triangle shows the marker for power-off, flaps up, the downward triangle indicates power-off, flaps down, and the circle represents the power-on, flaps up condition. The vertical order of the markers is reversed compared to the stall speed plot, where flaps-up tests show a lower lift coefficient compared to flaps-down tests. The power-on, flaps up stall tests show increased lift coefficient compared to the power-off tests at the same condition, likely because of the effects of prop wash over the wing root and tail. The Piper Lance shows a pattern different than other aircraft in that the estimated lift coefficient during power-on, flaps up stall test exceeds that for the power-off, flaps down stall. The Lance is the only one of the tested aircraft with a T-tail configuration, which may exhibit improved tail authority at high-power and high-angles of attack compared to the remaining conventional tail aircraft where the tail operates in the downwash of the wing.
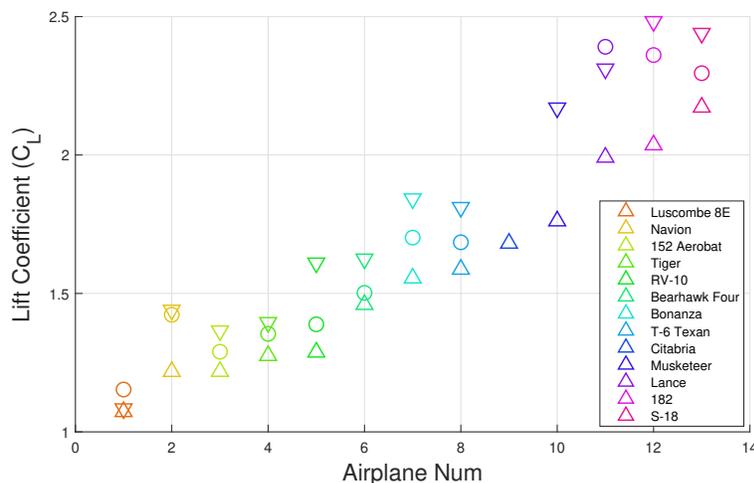
Fig. 9   Maximum Lift Coefficient Estimate At Stall

9

B. Takeoff Performance

Takeoff is the only mandatory maneuver on any flight, although measurement of takeoff distance is "some of the most difficult and costly flight test data to obtain" according to Kimberlin[16]. The takeoff process involves a transition of the aircraft from a ground vehicle to a flight vehicle by means of acceleration down a runway to a speed sufficient to permit wingborne flight. The takeoff rolling distance is minimized when the aircraft accelerates at the maximum-possible rate, which requires maximizing thrust forces and minimizing drag forces from aerodynamics and rolling friction.

The distance traveled during acceleration starting from rest varies with the square of the final speed, V_f, and is inversely proportional to the rate of acceleration, a, as in Equation 2,

$$S_g = \frac{V_f^2}{2a} \tag{2}$$

Equation 3 shows an approximation for the takeoff distance, S_g, with respect to aircraft weight, W, takeoff speed, V_{TO}, thrust, T, drag, D, rolling friction, μ, and Lift, L. The acceleration term from Equation 2 is replaced by an aggregate of the forces providing and resisting acceleration acting against the aircraft mass.

$$S_g = \frac{W}{g(T - D - \mu(W - L)_{avg})} \frac{V_{TO}^2}{2} \tag{3}$$

For tricycle-gear aircraft, the resting attitude of the aircraft on the wheels corresponds to a low angle of attack that is insufficient for developing the necessary lift for takeoff. However, the level pitch attitude applies thrust forces largely in the direction of acceleration while reducing drag forces resulting from high angle of attack. Conversely, the nose-up resting attitude of taildragger aircraft results in a misaligned thrust vector and excessive drag due to the high angle of attack during initial roll out. Taildraggers are balanced such that the tail is lightly loaded and starts to develop sufficient force to lift the tail even at low airspeeds. Once the tail is raised, a taildragger continues to accelerate at low angle of attack with the benefit of an aligned thrust vector and reduced aerodynamic drag.

Both types of aircraft, tricycle-gear and taildragger, will accelerate until reaching a speed sufficient for rotation and lift off. Takeoff rotation is an increase in pitch angle and angle of attack that permits the aircraft to increase the wing lift coefficient while already at V_{TO} or V_R, the takeoff or rotation speeds, respectively. The choice of V_{TO} for any aircraft is usually based on level flight stall speed, the minimum speed at which the aircraft can maintain a load factor of 1. Rotating at stall speed would cause the aircraft to achieve lift force equal to the weight, but that would occur at the critical angle of attack with the aircraft unable to produce any additional lift to achieve a vertical acceleration and climb out. The required takeoff speed, V_{TO} is taken by convention [16][17][18][19] to be 10% greater than stall speed, providing for a maximum load factor of $n = 1.21$.

$$V_{TO} = 1.1 * V_s \tag{4}$$

The stall speed of an aircraft is given by Equation 5 for any load factor, n. The level flight stall speed, used in the estimation of V_{TO}, is taken at $n = 1$.

$$V_s = \sqrt{\frac{2Wn}{\rho S C_{L_{max}}}} \tag{5}$$

Equation 6 shows the final estimate of takeoff distance by substituting Equation 5 into Equation 3. The quadratric dependency on weight is a result of the dual penalty on acceleration and on the lift force. Many of the terms in Equation 6 are constants, although thrust, drag, and the weight force exerted on the wheels all vary throughout the takeoff run. The 'avg' subscript indicates that the quantities used in the equations are the average values, respectively, over the takeoff run. A more precise estimate of the takeoff roll distance uses an integration of the time-varying quantities and includes the acceleration from a stop until the aircraft reaches V_{TO}, plus an additional term to account for the distance traveled during the rotation.

$$S_g = \frac{1.21 * W^2}{\rho S C_{L_{max}} g(T - D - \mu(W - L)_{avg})} \tag{6}$$

Equation 7 is used to estimate the takeoff distance from the flight test data. The takeoff speed is assumed to be 10% greater than the power-on, flaps up stall speed, V_{s2}, while a_{max} is average over a segment of the takeoff run with the peak acceleration. This value for the takeoff acceleration assumes that the thrust force does not diminish significantly over the

takeoff roll and that the combination of the aerodynamic drag and rolling resistance forces are largely constant. Both the takeoff speed and the acceleration are corrected for weight and altitude effects using standard correction factors[16].

$$S_g = \frac{(1.1V_{s2})^2}{2a_{max}} \tag{7}$$

The reconstructed takeoff distances are shown in Figure 10 along with published takeoff distances from the Aircraft Flight Manual for each aircraft. For certified aircraft, the published value shown represents the takeoff roll distance at the maximum takeoff weight at sea level with no wind on a level, paved runway. The reconstructed flight test values are corrected to these same conditions.
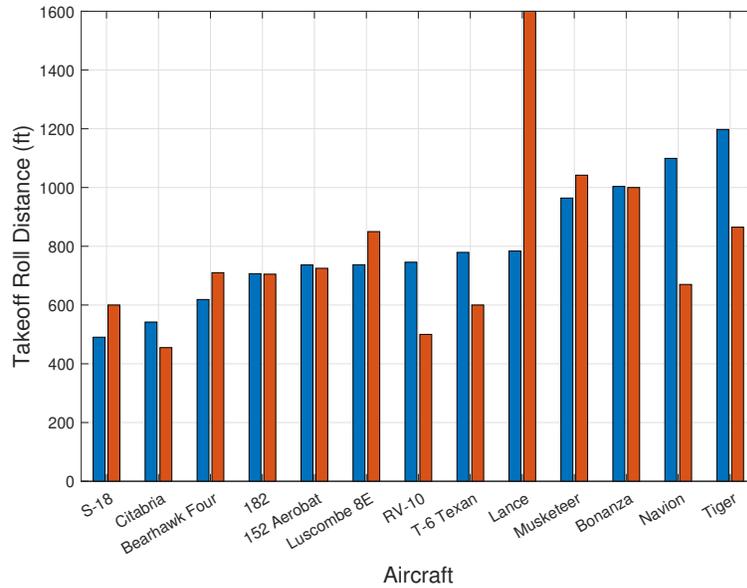

Fig. 10   Comparison of Reconstructed Takeoff Roll Distance (Blue) Compared Compared to Published Values (Orange)

Some of the takeoff distance estimates show close agreement with the published values, especially in the case of the Cessna 182, the Cessna 152 Aerobat, and the Beechcraft Bonanza. Most of the others show a difference of less than 10%, although there is significant overprediction of the takeoff distance for the RV-10, the T-6 Texan, the Navion, and the Grumman Tiger. A significant outlier is the Piper Lance, which showed a reconstructed takeoff distance of 800 feet, which is half of the published value of 1600 feet. That published value itself is substantially longer than the distances for all other aircraft.

C. Level Acceleration and Climb Performance

The level acceleration is an energy-based flight maneuver that can be used to rapidly determine aircraft performance over a wide speed range. The type of level acceleration performed for the 20-Minute Flight Test is adapted from recommendations by Kimberlin[16]. Pilots are asked to decelerate from cruise speed to slow flight, then apply maximum continuous power to accelerate the aircraft to the maximum level flight speed. Figure 11 shows a overlay of time histories for each of the test aircraft. Convergence times for the maneuver range from 70 seconds to 140 seconds, depending on the excess power profile and drag. The airspeed response during a level acceleration shows the range of airspeeds, from minimum to maximum, along with the rate of change of airspeed throughout that range. Additionally, the non-monotonic responses show issues with the quality of airspeed measurements or unsteadiness in the pilot technique. Pilots are asked to fly the level acceleration at a fixed altitude, although trim variations with airspeed can result in deviations in flight path angle and altitude.

Aircraft performance variation over the flight envelope can be estimated from the level acceleration flight data by computing specific excess power, P_s, using Equation 8. P_s describes the ability of the aircraft to either climb or
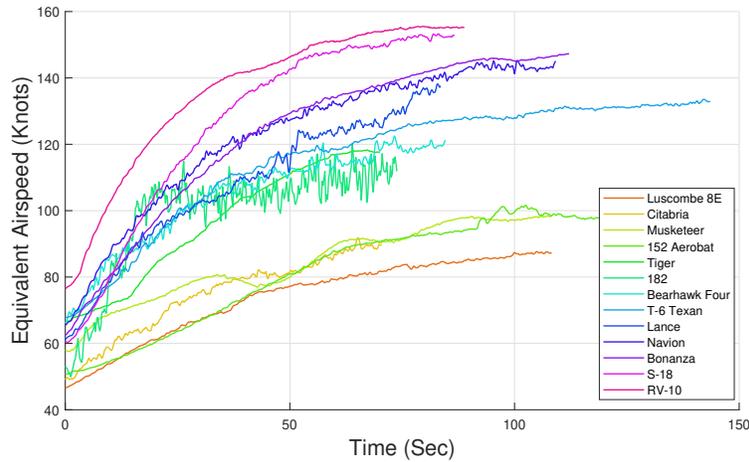
Fig. 11   Level Acceleration Time History

accelerate using excess power normalized by aircraft weight. The units of P_s are in distance per unit time and can be directly interpreted as the maximum climb rate or a maximum acceleration at a particular airspeed.

$$P_s = \frac{dH}{dt} + \frac{V_t}{g}\frac{dV_t}{dt} \tag{8}$$

The flight data instrumentation system includes redundant sensors to measure or estimate the flight path acceleration and altitude changes. Airspeed and altitude data are smoothed using a zero-phase forward-backward filter to reduce noise in the estimate of acceleration using differentiation.

Figure 12 shows the specific excess power for each of the test aircraft versus equivalent airspeed. The operational airspeed range is shown as the width of the peak curves. As the curve descends to zero, the aircraft has no excess power to continue accelerating and has reached its maximum speed. The peak of each curve occurs at the airspeed corresponding to the maximum excess power and maximum climb rate. From Equation 8, at a steady airspeed where $\frac{dV_t}{dt}$ is zero, the specific excess power reduces to:

$$P_s = \frac{dH}{dt} \tag{9}$$

The maximum P_s is equivalently the maximum rate of climb. At any airspeed faster than or slower than the peak, the aircraft is burdened by reduced excess power due to increased power required and, in turn, suffers a reduced maximum climb rate.

Aircraft flight manuals and pilot operating handbooks detail two critical climb speeds, V_y and V_x. V_y is the speed corresponding to the peak in specific excess power at which the aircraft climbs at the maximum rate. This airspeed and corresponding climb rate is used by the pilot to efficiently climb to altitude in minimum time. Pilots flying in terrain-constrained areas may prefer to climb at the steepest angle. V_x is the speed that corresponds to the tangent of the P_s curve with a line originating at the $P_s = 0$, $V_t = 0$ origin. Flying an aircraft at V_x provides the maximum P_s, and climb rate, with respect to airspeed. The aircraft then maximizes vertical speed with respect to airspeed, which in turn maximizes flight path angle and achieves the steepest angle of climb. V_y and V_x are indicated in Figure 8 as the circle markers on and preceding the P_s peak, respectively.

The number and type of aircraft that can be tested can be limited by the opportunistic nature of the 20-minute flight tests. The authors have tested additional aircraft as part of the UMKC Flight Test Engineering program. The specific excess power for all the propeller-driven aircraft is shown in Figure 13. The additional aircraft include several additional models from Cessna and Piper.

Comparisons of naturally-aspirated, light aircraft show that the flight performance is constrained to low, subsonic airspeeds. Flight at faster speeds is energetically expensive and, in most cases, prohibitive. Figure 14 shows how a very different type of aircraft compares to all others considered in this work. The colorful cluster toward the left of the plot shows the performance domain in airspeed and excess power for common propeller-driven aircraft. The pink line
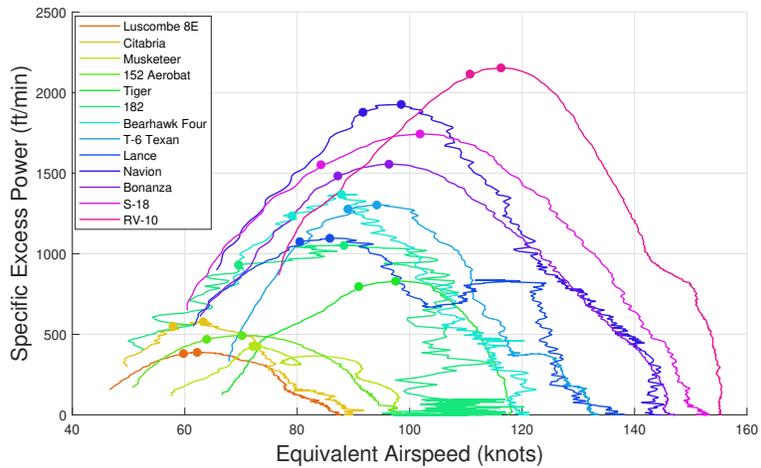
**Fig. 12   Specific Excess Power Computed During Level Acceleration**
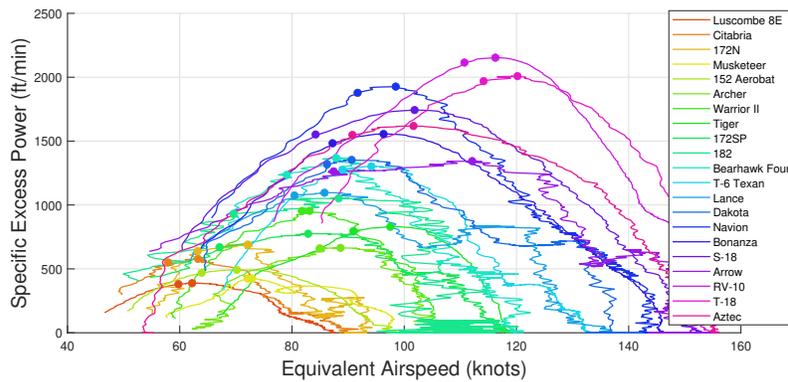
Fig. 13   Specific Excess Power for Propeller-Driven Aircraft Tested the Author

occupying the remaining part of the figure shows the performance capability of the TPS Northrop T-38 Talon. The minimum speed of this twin-engine jet exceeds the maximum speed of the other tested aircraft, whereas the maximum speed is in the transonic range for typical operation and supersonic when using afterburners. The authors flew on the flight tests used to generate the data in Figure 14 and assure the readers that these tests were strictly necessary in support of this work.

D. Control Response

The first flight for a student pilot usually involves a demonstration of the aircraft response to uncoupled controls. Students independently invoke the ailerons, elevator, and rudder to assess both the primary-axis response and the secondary-axis response that may require use of the other control surfaces for coordination. Pilots flying the 20-Minute Flight Tests are asked to similarly perform uncoupled doublets and triplets to the aileron, elevator, and rudder control surfaces. The pilots are instructed to perform a sharp input in each direction with no coordination from other control surfaces, then neutralize the controls and allow the aircraft oscillations to subside.

The flight data instrumentation system does not include measurements of stick position or stick force, so the data is unusable for system identification. A comparison of the responses across aircraft shows variations in the cross-axis coupling and the stability of the aircraft modes.
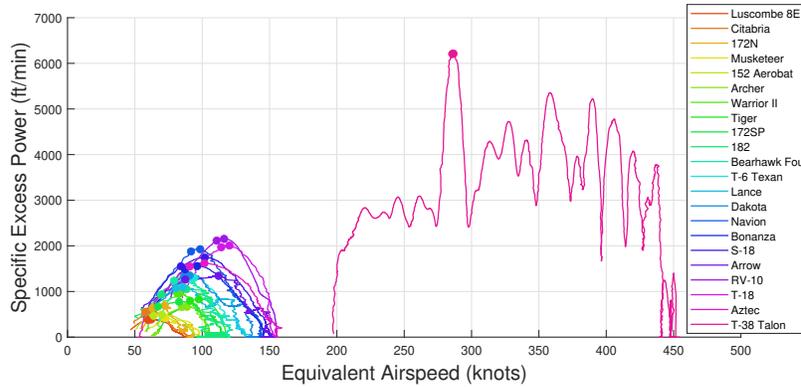
Fig. 14 Specific Excess Power for All Aircraft Tested the Author
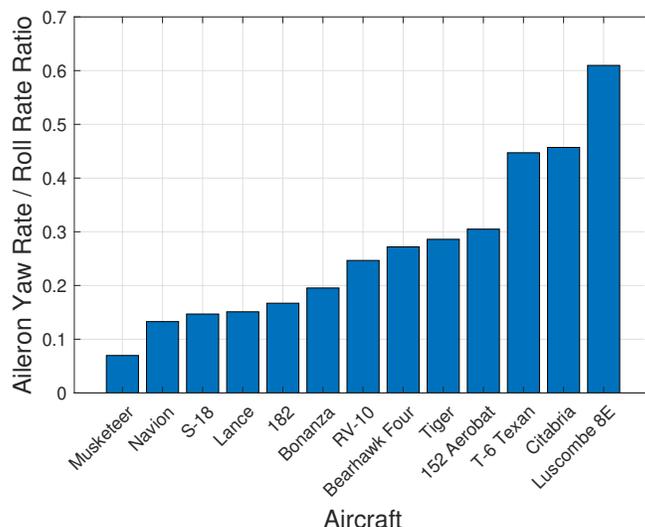
1. Response to Aileron Input

Figure 15 shows the overlayed time histories of roll rate and yaw rate responses to aileron doublets. Pilots are instructed to perform two or three pulse inputs to the aileron with no rudder coordination then neutralize the stick. The primary-axis response in roll rate varies from 10 deg/s to 70 deg/s. For each aircraft, aileron actuation yields a proverse roll response and an adverse yaw response. Roll rate converges at the conclusion of the aileron input, while yaw rate continues in a damped oscillation.
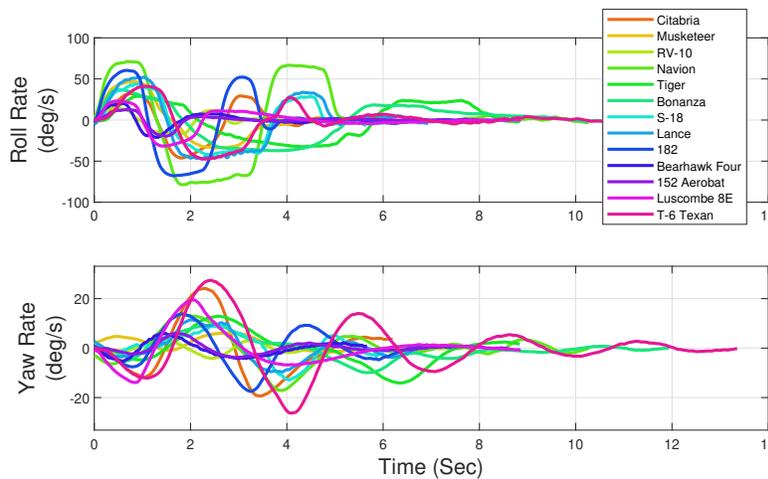
Fig. 15 Overlay of Roll Rate and Yaw Rate Responses to Aileron Doublets

The degree of adverse yaw coupling to aileron input varies with aircraft type. Figure 16 shows the amplitude ratio of adverse yaw rate to primary roll rate response. An amplitude ratio of 0.2 indicates that a right +10 deg/s roll rate results in a left -2 deg/s adverse yaw rate response. The smallest degree of coupling was measured on the Beechcraft Musketeer at 0.07 with the largest in the Luscombe 8E at 0.61. Adverse yaw, generally, is exacerbated for ailerons on aircraft with long-wingspan, high-aspect-ratio wings, particularly those without aileron differential deflection. Gliders exhibit substantial adverse yaw ratios exceeding 1. A large value of roll-to-yaw amplitude ratio necessitates more rudder input to maintain turn coordination. Pilots flying new aircraft frequently over-control or under-control rudder if the difference in roll-to-yaw amplitude ratio is large compared to the aircraft to which they are accustomed.

Volunteer pilots may be unaccustomed to performing uncoordinated control inputs, so the specific adverse yaw ratios may include inadvertent rudder coordination that could affect the results.

Fig. 16   Ratio of Adverse Yaw Rate to Proverse Roll Rate During Aileron Doublet

2. Response to Rudder Input

Rudder doublets are performed with the stick fixed and the pilots commanding a right-left rudder input. Figure 17 shows an overlay of time histories in primary-axis yaw with coupling to roll through sideslip and dihedral coupling. Damped yaw oscillations continue after the doublet as the pilots hold pedal-fixed inputs.
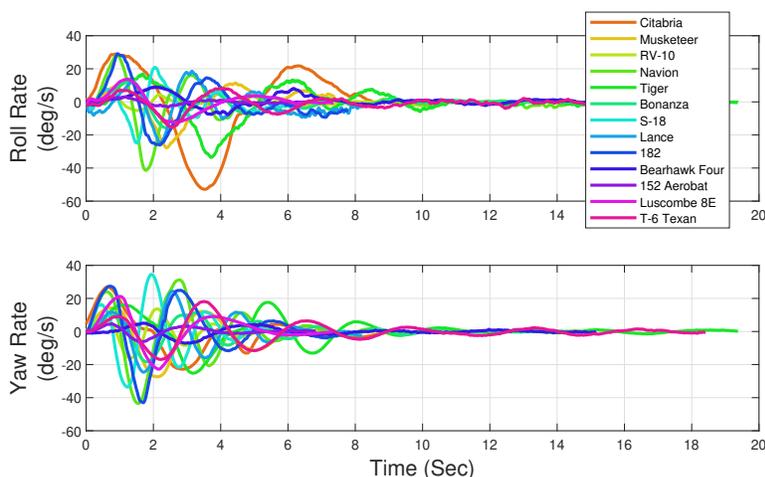

Fig. 17   Overlay of Roll Rate and Yaw Rate Responses to Rudder Doublets

Figure 18 shows the coupling between primary-axis yaw rate to secondary roll rate responses. The roll rate responses are proverse in directionality, where right yaw rate results in right roll rate. The secondary roll response is usually intended by the aircraft designer for stability and control, as opposed to the adverse yaw response which is considered undesirable. Response amplitude ratios range from 0.25 for the S-18 to 1.6 on the Citabria.

A large yaw-to-roll amplitude ratio is indicative of large lateral stability through dihedral or dihedral effect in the aircraft design. Pilots flying aircraft with such amplitude ratios may be able to fly the aircraft using rudder input alone without the use of ailerons. High-performance aerobatic aircraft often desire low coupling ratios such that primary-axis responses to aileron and rudder yield minimal cross-axis coupling.
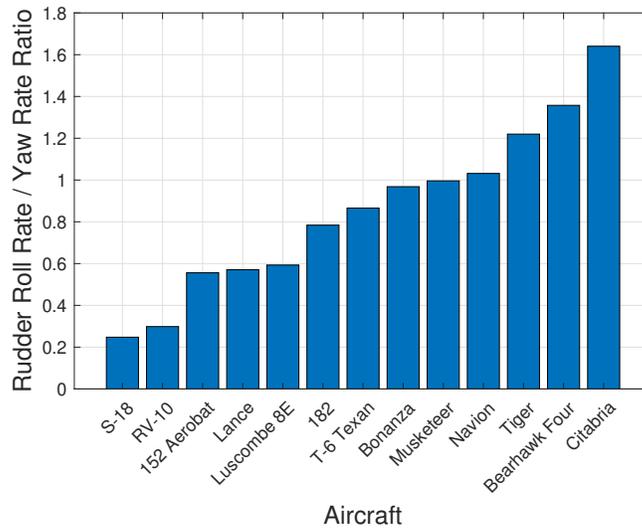
**Fig. 18　Ratio of Proverse Roll Rate to Proverse Yaw Rate During Rudder Doublet**
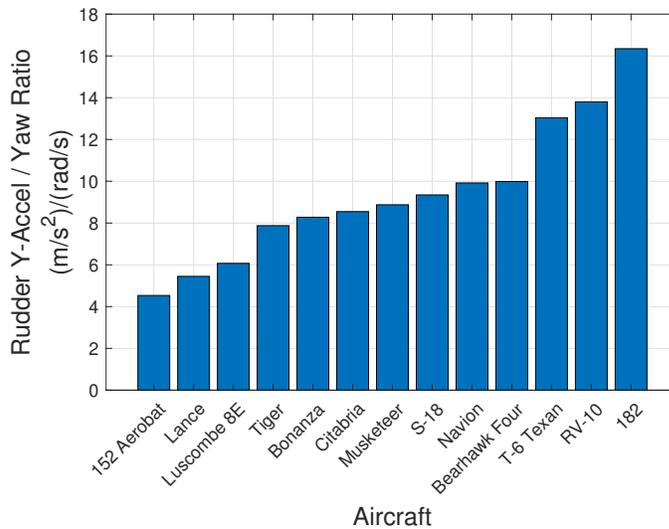
Fig. 19　Ratio of Lateral Acceleration to Proverse Yaw Rate During Rudder Doublet

E. Speed Ratio

Speed versatility is measured as the ratio of the maximum level flight speed to the stall speed. An aircraft with a large speed ratio demonstrates versatility by traversing distances quickly at high speed, yet remains able to land on short-length runways. The high-lift and high-drag devices on airliner wings, namely flaps, slats, and spoilers, all serve to increase the speed versatility. Designing an aircraft for high-speed often involves compromises that preclude slow landing approach speeds that would permit operations on short runways. Conversely, designing an aircraft for short-field operation requires design choices that restrict maximum level flight speed.

Figure 20 shows the speed ratio measured using the maximum level flight speed compared to the power-off, flaps down stall speed.
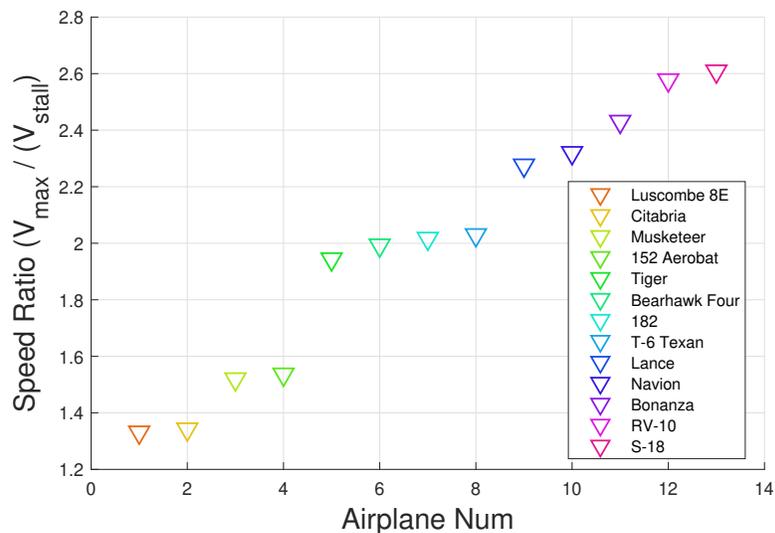
Fig. 20   Ratio of Maximum Speed to Stall Speed

VI. Summary

The 20-Minute Flight Test project evaluated the performance and handling characteristics of several general aviation aircraft flown by inexperienced test pilots using a hurried flight test methodology. The objective is not to show that manufacturer-published performance specifications can be easily recreated in the absence of a dedicated flight test campaign. Instead, the goal was to design a flight card that reduced the dependency on expert flying technique yet still resulted in usable information for pilots and engineers seeking an expedient evaluation.

For students of Aircraft Design and Flight Test Engineering, the project helps illustrate the influence of design choices by showing how aircraft perform at the boundaries of the flight envelope. An aircraft of a particular weight, for instance, has a takeoff acceleration constrained by the available propeller thrust. That aircraft will be required to accelerate along the runway until achieving takeoff speed, governed by the size of the wing compared to the weight. Once in flight, the aircraft speed, climb rate, and maneuverability will again be dictated by the design choices. All of this is obvious to the veteran aerospace engineer, but it remains an additional tool available to educators to convey the tradeoffs, complexity, and challenge of aircraft design.

A looming question in the evaluation of this work remains - how accurate are the results of the 20-minute flight test compared to manufacturer published values? The analysis in this paper showed that, in some cases, the estimates for takeoff distances, maximum speed, stall speed, and climb rate matched closely with handbook values. In other cases, the values are quite disparate.

Perhaps a more pressing question is whether there's a reasonable expectation that the results of these flight tests should reproduce manufacturer-provided performance specification? Some of the aircraft used in this study are more than 70 years old with many thousands of hours of operation. While all remain airworthy, all of them differ in some way from a factory-new aircraft. An aircraft ready for engine overhaul will have turned the propeller approximately 300 million revolutions. The propeller, while remaining serviceable, may be an inch or more shorter than new. Worn paint, new covering, repairs, updated systems, and modifications may result in performance changes even when assessed by flight test professionals. A sufficient goal is to assess the performance of a particular aircraft, aided by post-flight data analysis, even in the presence of admitted challenges in planning, piloting, and instrumentation.

It is appropriate to conclude this paper with an assessment of the promise borne into the name of the project and the title of this work. Just how long *are* the 20-minute flight tests? Figure 21 shows the actual duration of the so-called 20-minute flight tests, as measured from takeoff to landing. The majority of the test flights are completed in the range of 19 to 27 minutes, leading to the obvious suggestion that this project be retitled "The 20-ish-Minute Flight Tests". In practice, the actual maneuvers are easily conducted within 20 minutes, although air traffic control routing, distance from the airport to a suitable test area, aircraft speed, maneuver repetition, and pilot pacing are all factors that affect the actual flight duration.

The final factor that affects the flight test duration is the result of the combination of engineering ambitions with

17
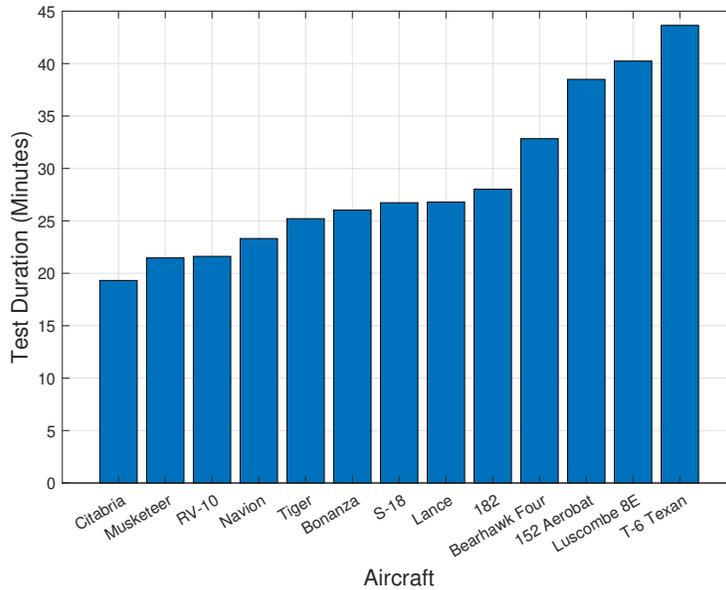
Fig. 21   Duration of 20-Minute Flight Tests

aviation enthusiasm. For many pilots, notably those with the longest flight durations in Figure 21, the test maneuvers were completed relatively quickly, leaving the pilot and the author(s) sitting at altitude wondering if there were a better way to take advantage of a lovely flying day than simply returning immediately to the airport.

VII. Acknowledgments

References

[1] "Flight Test Guide for Certification of Part 23 Airplanes," 2011.

[2] *Bellanca Citabria - Pilot's Operating Manual*, Bellanca Aircraft Corporation, 1973.

[3] Company, L. S. A., *Luscombe Silvaire SLSA-8 - Pilot Operating Handbook*, 2012.

[4] *Pilot's Operating Handbook - Cessna 152 Aerobat - Model A152*, Cessna Aircraft Company, 1978.

[5] Erb, R., "Bearhawk 20 Minute Flight Test," , 2023. `http://erbman.org/bearhawkbits/2303%2020%20min%20flight%20test.pdf`.

[6] *Navion Operation Manual, Fourth Edition*, Ryan Aeronautical Company, 1950.

[7] *Beechcraft Musketeer 23 - Pilot's Operating Handbook and FAA Approved Airplane Flight Manual*, Beech Aircraft Corporation, 1994.

[8] *Pilot's Operating Handbook and FAA Approved Airplane Flight Manual - Cessna 182*, Cessna Aircraft Company, 1979.

[9] *Pilot's Operating Handbook - Model AA-5B Tiger*, Gulfstream Aerospace, 1979.

[10] "Thorp Central - The S-18," , 2024. `https://www.thorpcentral.com/the-s-18`.

[11] "Vans RV-10 Specifications," , 2024. `https://www.vansaircraft.com/rv-10/#aircraft-details-1`.

[12] Jackson, A., *Bonanza V35 Pilot's Operating Handbook and FAA Approved Airplane Flight Manual*, Beech Aircraft Corporation, 1994.

[13] *Pilot's Operating Handbook and FAA Approved Airplane Flight Manual - Piper Lance II*, 1978.

[14] *Flight Handbook - USAF Series T-6D Aircraft*, Secretary of the Air Force and the Chief of the Bureau of Aeronautics, 1953.

[15] "14 CFR Part 23: Airworthiness Standards: Normal Category Airplanes," Accessed 2024.

[16] Kimberlin, R. D., *Flight testing of fixed wing aircraft*, American Institute of Aeronautics and Astronautics, 2003.

[17] Phillips, W. F., *Mechanics of flight*, John Wiley & Sons, 2010.

[18] Raymer, D., *Aircraft Design: A Conceptual Approach*, American Institute of Aeronautics and Astronautics, 2018.

[19] Corda, S., *Introduction to aerospace engineering with a flight test perspective*, John Wiley & Sons, 2017.

[20] Lee, W. F., "The TPS Barf Kit for New Jet Passengers," Personal Communication, 2024-7-9.

Appendices

A. Russ Erb's Bearhawk 20 Minute Flight Test

Authors' Note: This section is an excerpt of the report authored by Russ Erb following his flight test in the Bearhawk. The full report is available online[5].

A. Introduction

In the summer of 2022 I had the pleasure of meeting Mujahid Abdulrahim of the University of Missouri at Kansas City (UMKC). He was at USAF TPS working on a project for USAF TPS for the summer. He introduced me to his "20 Minute Flight Test" program that he had put together as a way to collect flight test data on various general aviation aircraft. These data could be used to better understand the capabilities of different aircraft types and to provide interesting projects for his students at UMKC. Of course, there is suspicion that this is just a clever way to convince other pilots to take him flying in their airplane, an idea that I fully support and wonder why I didn't think of it.

To support the 20 Minute Flight Test, Mujahid had a strap-on instrumentation system and two GoPro cameras. Since the Bearhawk was equipped with its own instrumentation system, this report is written to record the results (including maneuvers that I never got around to measuring before) and to provide truth data for Mujahid to compare his results against.

B. Profile Description

The profile starts on the ground with an interview of the pilot. The pilot is asked the following questions:
1) How long have you been flying?
2) How much total time have you flown? How many hours in this aircraft?
3) Why do you fly this aircraft?
4) What is your typical flight mission(s)?
5) What is one (or more) of your favorite aspects about this aircraft?
6) What is something you would like to improve about this aircraft?
7) What is the most interesting airplane that you have flown?

Photographs are taken at eight locations radially around the aircraft, as well as of the wing airfoil, dihedral, wing control surfaces, tail control surfaces, and the instrument panel. This being a modern flight test program, photographic data include a pre-mission selfie with the airplane and a post-mission selfie.

The flight profile consisted of
1) Normal takeoff
2) Climb at maximum angle of climb (Vx), maximum rate of climb (Vy), and cruise climb
3) Level Acceleration, slowing from cruise speed to minimum level flight speed, then accelerating to maximum speed
4) Control response, consisting of doublets in pitch, yaw, and roll
5) Turn response, consisting of a 90 degree right turn, followed immediately by a 90 degree left turn, and a 360 deg steep turn
6) Stalls in the cruise configuration, power off; in the landing configuration, power off; and in the cruise configuration, power on
7) An optional maneuver at the pilot's discretion that is unique to the aircraft or shows off some special capability
8) Normal landing.

C. Is it really 20 minutes?

This flight was flown on 2 August 2022 from Rosamond Skypark (L00). Takeoff was at 1035L, and the last maneuver (stalls) was completed at 1103, for a total elapsed time of 28 minutes. No effort was made to fly the profile super efficiently, and breaks were taken as required to allow the engine to cool down to acceptable temperatures. The entire mission lasted for 1.0 hour, but this included additional time for Mujahid to try his own hand at flying the airplane.

D. Instrumentation

The Bearhawk instrumentation included a Dynon D10A EFIS, which recorded air data, attitudes, lateral acceleration, and yaw rate from internal sensors at a rate of 1 Hz. The D10A also recorded GPS location and speed data as provided by the Garmin GNS 480. The D10A clock was synced to GPS time by way of the GPS data messages.

Engine data, including manifold pressure, RPM, outside air temperature, cylinder head temperatures, exhaust gas temperatures, voltage, and amperage were recorded in the EDM 930 at a rate of 0.5 Hz (every 2 seconds). The EDM 930 clock was synced to GPS time immediately before the flight.

E. Takeoff

Takeoff Conditions:
Gross weight: 2375 lbs
Wind: minimal cross wind, no significant headwind
Temperature: 90 deg F (yes, at 1035L)
Initial Altitude: 2534 ft

All altitudes were recorded with local altimeter set. The local altimeter setting was not recorded. (Bad FTE technique) The altitude reported was estimated to be within 100 feet of pressure altitude. The field elevation was 2415 feet. The takeoff altitude was recorded at 2534 feet. The difference was suspected to be from a calibration error in the Dynon altimeter, which is known to vary relative to the round dial altimeter. Additionally, the source for the altimeter setting on the local CTAF was known to give a measured altitude higher than the known field elevation. However, the differences between the measured altitude and the actual pressure altitude were assumed to have minimal effect on the

aircraft performance.

Measured Data:
Rotate Speed: 60 KIAS
Liftoff Speed: 75 KIAS
Time from brake release to liftoff: 20 sec
Time from rotate to liftoff: 4 seconds

Calculated Data:
Density Altitude: 5049 feet
Liftoff true airspeed: 80.85 KTAS
Takeoff ground roll distance assuming a constant acceleration: 1364 feet
Takeoff ground roll distance from latitude/longitude of start point and liftoff point: 1335 feet

The takeoff distances measured by two different techniques are very close to each other (within 29 feet, about 2 per cent), lending credibility to the result. Figures 22 and 23 show the altitude and airspeed measurements, respectively, used to estimate the takeoff distance.
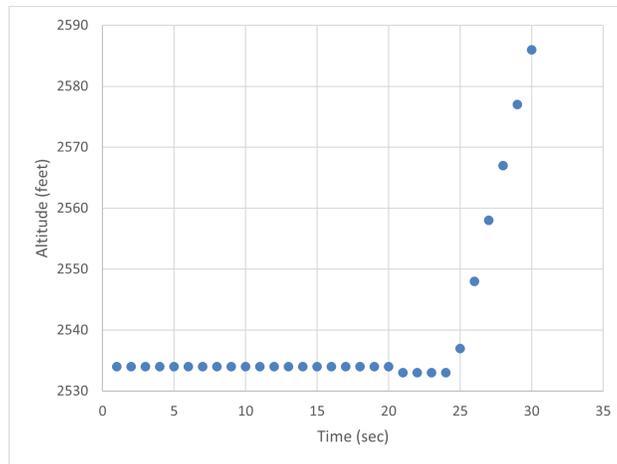

Fig. 22   Altitude During Bearhawk Takeoff
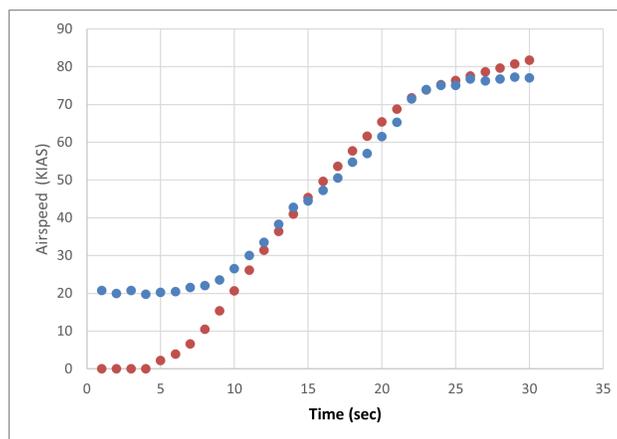
Fig. 23   Airspeed During Bearhawk Takeoff

F. Climb Pitch Attitudes

Figure 24 shows the relative pitch attitudes called out in the previous pages. The fuselage side view is shown, along with a line representing the sightline from the pilot's eye position to the top of the cowling. In the Best Angle of Climb and Best Rate of Climb attitudes, this sight line is above level, meaning that the horizon in hidden from view behind the cowling. In the Cruise Climb attitude, the sight line is essentially level, representing the horizon lined up with the top of the cowling. In the level flight attitude, the sight line is below the horizon, representing a view of the terrain ahead.
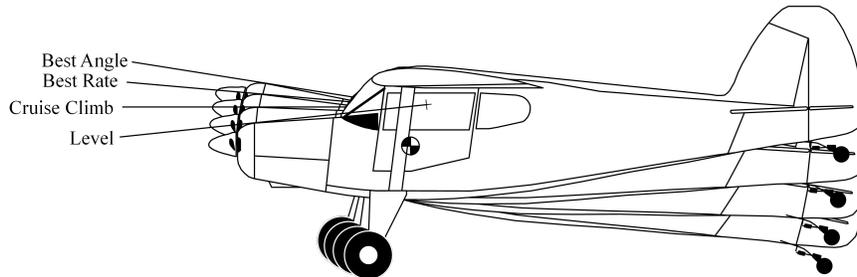
Fig. 24   Bearhawk Climb Pitch Attitudes

G. Control Response

Control response was evaluated at approximately 6500 feet altitude at normal cruise speed, approximately 107 KIAS or 122 KTAS.

1. Rudder Doublets

Rudder doublets excited the Dutch Roll mode. After controls release, there were three to four overshoots, estimating a damping ratio of about 0.4 to 0.3. The response was more rolly than most gliders, with a Phi to Beta ratio of around 1. There was sufficient lateral stability to be able to pick up a wing (cause a roll) with rudder. This indicated a noticeable dihedral effect, which was expected with a geometric dihedral of 1 degree on each side plus the high wing configuration. The small vertical tail and rudder resulted in relaxed directional stability, which led to the reduced damping. Of interest, this is reminiscent of the relaxed directional stability seen in aircraft of the 1930s, to which this fuselage and vertical tail design is similar.

2. Elevator Doublet

Initially it was not possible to do a pure pitch doublet. A small pull resulted in the expected increase in pitch angle. However, a small push that was thought to be of the same magnitude resulted in a quicker unload and pitch down than expected. The natural reaction was a second pull to stop the uncomfortable reduction in load factor and pitch rate. Freezing the stick stopped the impending PIO. On a later flight, a different technique was tried, pushing first, then pulling. This time there was not a feeling of impending PIO. There was movement in the nose with no overshoots. The resulting force of the push and pull was less than what was used before. Trying the same force in a pull-push created the similar results. The problem appeared to be that the airplane was very responsive to pitch inputs. A large pitch input could be made in the pull without being uncomfortable. However, a large pitch input in the push unloaded the load factor faster than expected, thus being uncomfortable. There was no residual motion following the forced response, showing that the short period was heavily damped.

3. Aileron Doublet

An aileron doublet caused the expected response in roll. With no coordinating rudder input, the adverse yaw resulting from an aileron doublet excited the Dutch Roll with the same damping results as the rudder doublet.

H. Stalls

Stalls were demonstrated by slowing in level flight at approximately 1 knot per second. Stalls were indicated by uncommanded pitch or roll motions. Predicted airspeeds came from previous testing where airspeeds were read from

Configuration	Predicted Airspeed	Measured Airspeed	AOA at Stall (Pct)
Flaps Up, Power Off	51 KIAS	55.5 KIAS	77
40 deg Flaps, Power Off	46 KIAS	51 KIAS	73
40 deg Flaps, Power On	46 KIAS	51 KIAS	43

Table 2   Bearhawk Stall Testing Results

the round dial airspeed indicator. Measured airspeeds for this testing were read from the Dynon D10A recorded data.

One stall was accomplished in the cruise configuration with the flaps up and power idle. Two stalls were accomplished with three notches of flaps (40 degrees) and power idle. Stalls were not accomplished in the cruise configuration with power on. Unlike a trainer aircraft with low excess power, where power on stalls result in a moderate pitch angle, the excess power available in the Bearhawk at stall speeds would result in uncomfortably high pitch angles, higher than the pitch angles seen during the Best Angle of Climb testing. While power on stalls are normally practiced to simulate getting slow after takeoff, the high pitch angle possible in the Bearhawk should warn the pilot that he is doing something wrong long before getting to an actual stall.

Angle of Attack measurements were taken from the Dynon D10A angle of attack instrumentation, which was derived from pressure measurements. For each stall, a higher angle of attack was seen shortly before the stall while slowing than was seen at the actual stall break.

All stalls were very benign, with only small uncommanded motions. Recovery was simple and quick by releasing back stick force. Controllability was never in question.